



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Technical Controversy and Ballistic Missile Defence

Citation for published version:

Spinardi, G 2013, 'Technical Controversy and Ballistic Missile Defence: Disputing Epistemic Authority in the Development of Hit-to-Kill Technology', *Science as Culture*. <https://doi.org/10.1080/09505431.2013.768224>

Digital Object Identifier (DOI):

[10.1080/09505431.2013.768224](https://doi.org/10.1080/09505431.2013.768224)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Science as Culture

Publisher Rights Statement:

© Spinardi, G. (2013). Technical Controversy and Ballistic Missile Defence: Disputing Epistemic Authority in the Development of Hit-to-Kill Technology. *Science as Culture*. 10.1080/09505431.2013.768224

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Technical Controversy and Ballistic Missile Defence: Disputing Epistemic Authority in the Development of Hit-to-kill Technology

Abstract

Public debate about Ballistic Missile Defence (BMD) has long centred on the question of feasibility, particularly as regards the realism of testing. Thus BMD opponents have argued that flight-tests are insufficiently similar to operational use to provide a reliable guide to real-world performance. However, an in-depth account of the development of US hit-to-kill technology – an approach to BMD that relies on the direct impact of an interceptor on the enemy missile warhead - reveals a far less-recognized issue: some BMD supporters have specific technical doubts which centre on the design of the current system rather than on its testing. These concerns hinge on contrasting claims to epistemic authority between two camps of BMD supporters. On the one hand, advocates of space-based BMD oppose the current system on in-principle conceptual grounds. On the other hand, some BMD supporters close to the development of ground-based hit-to-kill technology claim that the empirical evidence from testing shows that the current design is suboptimal because it is the outcome of bureaucratic politics compromise between the two camps. Although the battle for epistemic authority has swung in favour of the latter hit-to-kill supporters recently, the lack of operational experience with a defence against nuclear-armed ballistic missiles means that further disputes are likely. So long as empirical knowledge claims rest solely on testing, they are unlikely to prove sufficiently politically compelling to silence advocates of space-based defence.

Key words: Missile defence, testing, military technology

Introduction

At 7.02 pacific daylight time on October 2, 1999 a Minuteman Intercontinental Ballistic Missile (ICBM) was launched from Vandenberg Air Force Base in

California. Heading west, the missile released a mock warhead and a decoy balloon made of a reflective synthetic material. About twenty minutes later another Minuteman, this time carrying a homing interceptor known as the exo-atmospheric kill vehicle (EKV), was launched from the US missile range at Kwajalein Atoll in the Marshall Islands, 4300 miles west of the California coast. Another ten minutes later, 3,000 miles from California and 140 miles above the ocean, the kill vehicle achieved a direct hit on the target. With a closing speed of 16,000 miles an hour, the impact was apparently decisive. According to a spokesman for the Ballistic Missile Defense Organization, 'the flash from the impact was spectacular' and the target was 'totally pulverised' (Stevenson, 1999).¹

Such a successful interception in a flight-test was an impressive achievement, but it left many questioning whether this hit-to-kill ballistic missile defence (BMD) technology would work in operational use (I will also refer to this as real-world use).² One success did not mean the system was reliable, and in fact the next two tests would be failures, as would a significant number over the following decade. In addition to concerns about reliability, critics expressed more fundamental doubts about whether even a series of successful tests provides convincing evidence about operational performance.

The main such critique came from opponents of BMD with the Union of Concerned Scientists (UCS) arguing that these flight-tests were 'not conducted under operationally-realistic conditions' (Gronlund et al, 2001, p. 14). In

¹ This account is based on Graham (2001), pp. 187-88; Stevenson (1999); Rick Lloyd, 'National Missile Defense – IEC was there!', <http://www.iechome.com/news/110099.htm>, accessed 30/1/08.

² It appears that the intercept was fortunate as the kill vehicle had drifted off target and only recovered by locking on to the balloon decoy which happened to be close to the target. See Dao (2001).

particular, these critics contended that the flight-tests were insufficiently challenging because they did not take account of likely enemy countermeasures (Sessler et al, 2000). Such criticism from longstanding opponents of BMD deployment is not surprising. However, as this paper will describe, doubts about the feasibility of this hit-to-kill technology are not restricted to BMD opponents, and the debate about feasibility hinges on more than just concern over the credibility of flight-tests.

Controversy over technical feasibility has long been at the heart of debates about BMD (although it is not the only concern with many opponents also arguing that deployment would be undesirable) and has been a persistent issue despite decades of development. However, this topic has attracted little attention from STS scholars (a notable exception is Slayton, 2003). There are many studies of the politics of BMD technology (recent examples include Peoples, 2009; a classic study is Yanarella, 1977), but these make little attempt to open the black box.

The aim here is to address this gap in our understanding of the debate over BMD feasibility through a detailed historical case study describing the development of hit-to-kill technology. What role has testing played in providing evidence of the potential success of BMD, and why - despite decades of development - have test results failed to convince critics of BMD feasibility? Why have the fortunes of hit-to-kill technology fluctuated over the years? And why is it that some BMD supporters are critical of the hit-to-kill Ground-based Midcourse Defense (GMD) deployed by the administration of G. W. Bush (and continued under Obama)?

Testing, Missile Defence, and Knowledge Claims

Testing plays an important role in the development of many technologies, and is a key source of knowledge about performance (MacKenzie, 1989; Pinch, 1993; Downer, 2007). Flight-testing has been central to debates about the feasibility of BMD technology because it is seen as providing the empirical feedback that is

closest to actual use. This matters because BMD technology has had little operational experience (the exception being the use of short-range Patriot systems against non-nuclear threats in the two Gulf conflicts in 1991 and 2003).

Public controversy over the flight-testing of hit-to-kill technology (eg Gronlund et al, 2004) has focussed on two main concerns: that the flight-tests have not been successful enough to justify a decision to deploy such a BMD system, and that even successful tests (i.e. ones in which a direct hit on the target has apparently been achieved) do not provide satisfactory evidence because these tests are insufficiently representative of real-world conditions. Rather than concentrating on the failures *per se* – which they acknowledge are a normal part of the learning process in developing a challenging technology – these BMD critics question the relevance of the tests as an indicator of real-world performance. The central issue is thus the role of similarity judgements as analysed by MacKenzie (1989) in his study of missile flight-testing.

Concern about whether testing is sufficiently representative is at the heart of many technological controversies: with regulation of genetically modified crops, for example, hinging on ‘disputes about how to simulate realistic conditions of commercial use’ (Levidow, 2001, p. 866), or the safety of drugs being contested because ‘a great deal of uncertainty characterizes attempts to extrapolate the results of controlled clinical trials to future clinical practice’ (Abraham and Sheppard, 1999, p. 807). However, as MacKenzie (1989, pp. 413 & 415) argues: ‘Any test, or set of tests, is always open to challenge’, and thus ‘debates about testing are *potentially* endless’. Credibility rests on similarity judgments, and critics can always argue that tests are insufficiently similar to real use. Whether such disputes occur depends on social interests, on whether there is a ‘significant group with an interest in defeating the knowledge claims made as a result of an experiment or test’ (MacKenzie, 1989, pp. 415-16).

This would suggest a simple dichotomy in which opponents of a technology question the value of tests in order to dispute claims about technical feasibility whereas supporters are less critical. It is thus not surprising that BMD opponents such as the UCS have focussed on what they see as deficiencies in the testing of hit-to-kill technology. However, what is surprising is that some BMD supporters also doubt the efficacy of the current GMD hit-to-kill system. Moreover, these insider critiques hinge on broader epistemic issues: disputes not just about how knowledge is obtained (eg whether tests are representative), but also over what type of knowledge is considered most credible.

Specifically, the lack of operational experience with BMD technology undermines testing's epistemic credibility because as Downer (2007, p.9) argues in his paper on jet engine testing, the credibility of tests rests on them being 'designed to be representative of real-world conditions'. But with no operational use of BMD against nuclear-armed ballistic missiles, the real world must be constructed. It is not self-evident in nature, and instead the technology must be tested against likely operational scenarios in what can be seen as a virtual real world. There is thus a conceptual step that precedes the collection of empirical data from flight-tests; a model of how a defence should operate must first be constructed.

This weakens claims that BMD testing can, so to speak, directly interrogate nature. As Bloor (2005, p. 303) has put the argument in another context: 'When we say we compare the model to reality we are actually comparing the model to a reality interpreted through the model'. Knowledge about BMD technology relies on deduction from theory as well as inductive inference from testing (MacKenzie 1996). Indeed it is the battle for what Slayton (2003, p. 357) calls 'epistemic authority' between competing knowledge claims drawing on deductive and inductive sources that lies at the heart of debates about BMD feasibility.

However, this battle over epistemic authority does not happen in a political vacuum. As Bloor (2011, p. 403) writes in his masterly account of the

development of knowledge about the aerofoil, 'the actors involved were not detached intelligences moving in an abstract world of thoughts, theorems, and deductions.' Knowledge claims are powerful resources, but the actors deploying them operate within material and political constraints. In particular, in this case they operate in a world of bureaucratic politics, with the bounded rationality, routinised behaviour, and organisational conflict and compromise that characterise developments in US military technology (eg Armacost, 1969; Sapolsky, 1972; Greenwood, 1975; Spinardi, 1994).

Understanding disputes about the feasibility of the technology used in the current GMD system - with interceptor missiles deployed in Alaska and California – thus requires a historical perspective. A snapshot of just one episode in the history of the missile defence debate would only describe the particular knowledge claims about feasibility at that point, but would not explain how those beliefs came into existence, or how they co-evolved with the political context and technological developments. This paper thus follows a historical sociology approach, as used by MacKenzie (1990) in his study of missile guidance technology, drawing on interviews with some of the technology's developers to provide the first detailed account of the evolution of hit-to-kill technology. Most of these interviews were conducted under conditions of anonymity. Some have agreed to be named, but others have not. All cited either worked for the Army missile defence operations at Huntsville, Alabama or for one of its contractors.

The First Phase - 1955-75

To understand the debate over the feasibility of the current GMD system we need to go back to when the US first began serious work on BMD technology. Although the development of the German V2 ballistic missile during World War II led to post-war US BMD research, this only began to gather pace in the mid-1950s as the prospect of a Soviet Intercontinental Ballistic Missile (ICBM) started

to loom large. As with the development of missiles (Armacost, 1969), there was inter-service rivalry over organisational control of the BMD mission, with the US Army winning control in 1958 (Walker et al, 2003, p. 27).

Thereafter, the Army developed a system using ground-based interceptor missiles armed with nuclear warheads and controlled by radar. Other concepts for BMD were also mooted, however, and space-based approaches such as BAMBI (Ballistic Missile Boost Intercept) found favour within the Air Force. These alternative approaches had the organisational benefits of being different from what the Army was doing, and of potentially offering a role for the Air Force in missile defence. Their feasibility was examined by the Advanced Research Projects Agency (ARPA) that was set up in 1958 in the aftermath of the launch of the Soviet Sputnik satellite.

ARPA was not convinced. Jack Ruina, ARPA Director 1961-1963, later recalled: 'I always thought that it was a looney idea. I don't know why we continued it ... BAMBI brought in all the nuts out of the woodwork' (Barber, 1975, p. V-19). Nevertheless, the basic idea behind BAMBI was influential, and the conflict between those who supported such space-based approaches (originally aligned with the Air Force) and those who preferred ground-based interceptors, as developed by the Army, would shape the development of BMD technologies over the following decades.

This long-standing dispute hinges on the perceived challenges and benefits of each approach. The key feature of space-based BMD is that in principle it can intercept missiles soon after they take off, in their *boost phase* while the rocket boosters are still burning. This has the great advantage that the payload of multiple warheads and decoys has not yet been released. It thus appears to solve one of the major challenges of BMD – how to discriminate warheads from decoys during their flight outside the atmosphere where objects of different weight travel at the same speed. However, the boost phase only lasts three or

four minutes, making timely execution of such a defence extremely challenging. Moreover, spaced-based BMD systems need to be within reach of their targets, but because satellites (other than those in the geosynchronous orbit at about 36000 km altitude) move across the earth's surface, it would be extremely expensive to put sufficient such systems into orbit.

By contrast, the Army approach of ground-based interceptors relied on *midcourse* interception, carried out during the approximately twenty minutes that intercontinental range missile warheads travel above the atmosphere, and does not face such extreme time constraints. However, the challenge for midcourse interception is that light-weight decoys can in principle be designed to mimic the radar profile of the reentry vehicles that carry nuclear warheads, thus posing a critical problem of discrimination.

The significance of these differing concepts of missile defence is that the dispute about their in-principle advantages has been a persistent influence on the way that BMD technology has been developed. Although the Army won the initial political battle, space-based advocates continued to challenge the consensus around ground-based midcourse interception. Interests formed around organisational allegiances based on the different BMD concepts, though it was only the Army, with its mandate to develop anti-missile technology, that could back up conceptual claims with empirical evidence.

The Origins of Strategic Hit-to-Kill Technology

The Army's ground-based, nuclear-armed Anti-Ballistic Missile (ABM) technology was deployed in the Safeguard system in 1975, but this was cancelled almost immediately (Spinardi, 2010). Although testing was considered to have demonstrated success in intercepting target reentry vehicles, doubts about overall system effectiveness, along with the negotiation with the Soviet Union of

the Anti-Ballistic Missile treaty (allowing only limited deployment), made Safeguard politically unsustainable. A particular concern was its use of nuclear warheads - designed to disable enemy warheads with the radiation they emitted. These were necessary because command guidance using ground-based radar could not get the interceptors close enough to enemy reentry vehicles for conventional explosives to be effective. However, not only did the use of nuclear-armed interceptors contribute to local political opposition to their basing, but they also raised operational concerns. Nuclear detonations were expected to produce radar black-out in which portions of the sky would be rendered opaque to radar. This was a particular problem for Safeguard because each site had only one radar to control all its defensive missiles, and its effectiveness could therefore be quickly degraded as a result of nuclear detonations.

If feasible, a non-nuclear approach to missile defence thus had attractions both politically and operationally. The key requirement was better guidance and one possible approach was to use homing techniques based on semiconductor materials sensitive to infrared radiation. The potential of long-wave infrared (LWIR) detectors had been highlighted in a 1961 paper by Henry Swift of the Santa Barbara Research Institute (a research organisation of the Hughes aerospace company). Even using the limited materials of the time (lead selenide and copper-doped germanium), Swift demonstrated that if cryogenically cooled and operated above the atmosphere these detectors could achieve very long detection ranges. For example, a copper doped germanium detector, when used with a 5 inch aperture telescope, could detect a target of 300 degrees Kelvin (i.e. warm room temperature) against the much colder background of space at 1300 miles.³

³ Cited in Bill Davis, 'BMD Technology Advances', Paper presented at the 40th Anniversary Celebration of the US Army Space & Missile Defense, May 21, 1997. My thanks to Bill for providing with a copy of this paper. See also Price (2009: 245).

Infrared homing was considered in a wide-ranging study of promising new BMD approaches, known as the Newport Beach Study, carried out in 1968, and this led the Army's Advanced Ballistic Missile Defense Agency (ABMDA) to sponsor a further study called LORAH (Long Range Area Homing) in which four companies - Lockheed, Boeing, McDonnell Douglas and LTV - were chosen to investigate optical homing (Wendell Mead interview, 29.11.06). The use of small nuclear warheads was still under consideration in LORAH, but a key conclusion of the study was that infrared homing technology could achieve sufficient accuracy to make their use unnecessary (Dave Montague interview, 02.03.07).

The Homing Overlay Experiment

The first attempt to demonstrate non-nuclear hit-to-kill of strategic (i.e. intercontinental) warheads started in 1976 in the Homing Overlay Experiment (HOE) (GAO, 1994, p. 8). This drew on another programme, the Designating Optical Tracker (DOT) initiated the year before, that culminated in five flight tests between 1978 and 1982 and was reported to have 'demonstrated that a LWIR sensor could discriminate, designate and track a reentry vehicle' (Walker et al, 2003, p. 90). The Army sought authorisation for HOE from Secretary of the Army John Walsh, whose initial reaction was sceptical. Given that the previous BMD technology, Safeguard, had required the use of nuclear warheads with a lethal radius of about a mile, it seemed implausible that the Army now claimed to be able to achieve a direct hit. Bill Davis, then Deputy Director of ABMDA, recalled that 'it was kind of a hard sell because it's counter-intuitive. We were using big nuclear warheads. All of a sudden we don't have to use any warhead' (Interview, 29.11.06). Walsh insisted that a further year's simulation work be done to confirm the credibility of hit-to-kill, before agreeing to authorise HOE (Davis interview, 26.10.08).

Lockheed won the competition for HOE in August 1978 based on a bid that emphasised the use of existing technology where possible – Lockheed's HOE

programme manager, Dave Montague, recalled that their proposal claimed '85% flight proven hardware' (Interview, 29.11.06). HOE was thus not so much about technology development as technology demonstration: 'We put together for the experiment ... piece parts that we [had] in our arsenal ... without having to invent new machinery beyond ... the crucial piece, the optical sensor and the mechanism that controlled that sensor in the air' (GAO, 1994, p. 31). The only significant areas that required new technology were the infrared sensor, its associated cooling system, and the guidance system.

Given that HOE was intended to demonstrate something that had not been done before (and many doubted was possible) it made sense to over-design key capabilities. In particular, the aperture of the infrared telescope exceeded that indicated by simulations: 'you can calculate what the infrared signature's going to be but if you doing an experiment to prove something you just go a little bigger and collect more photons and be sure you're going to achieve your main objective' (Interview, 29.11.06). In fact, HOE was able to see reentry vehicles at distances of hundreds of miles. The popular way of describing its capabilities in unclassified terms was that: 'We could see a normal ice cube out of a refrigerator at 75 miles' (Interview, 29.11.06).

One of the key choices to be made for an infrared homing interceptor is the semiconductor material used for the focal plane detector. The main alternatives are silicon and mercury cadmium telluride (also known as Mercad Telluride). Silicon has a number of major advantages and one big disadvantage. Its greater sensitivity (it has a higher 'noise equivalent radiance') gives longer acquisition range, it detects a wider range of infrared frequencies, and it is easy to integrate with other silicon components. However, the one significant downside with silicon is that it needs to be cooled to very low temperatures to be effective in detecting missile reentry vehicles in their mid-course. Whereas 'Mercad' is effective at about 70 degrees Kelvin, silicon requires a temperature as low as 10 degrees Kelvin. At the time the availability of silicon semiconductors capable of detecting

the appropriate wavelengths gave it the edge (Montague interview, 29.11.06). Mercad was also hard to produce in sufficient quantities to give a large uniform focal plane.

A major part of the problems with HOE development stemmed from this cooling, which was achieved by blow down in which a cold gas is blown onto the focal plane. Typically this is done by expanding a suitable liquid (such as liquid helium or nitrogen) through a small aperture to produce the Joule Thomson effect. In HOE this used liquid helium to achieve low enough temperatures and even then the system could not do this on the fly during launch countdown and so cooling had to be done on the ground prior to launch.

The HOE programme manager described the testing approach as 'fly a little, learn a little', with the three main aims of HOE being to determine whether the kill vehicle could see the target with infrared detectors, and if so, could it get close to it, and if so, could it kill it (Interview, 29.11.06). In order to enhance the probability of a kill, HOE incorporated an unfurlable umbrella-like structure (see Figure 1). Four flight tests were planned with the target reentry vehicle launched on a missile from Vandenberg Air Force Base in California and the HOE interceptor launched from Kwajalein in the Pacific. Initially the 'fly a little, learn a little' approach was considered successful because useful information was learned from flight-tests despite their overall failure. However, this approach came under strain after the first two tests failed to hit the target.



Figure 1. Homing Overlay Experiment Test Vehicle. Photograph reproduced with permission of the National Air and Space Museum, Smithsonian Institution.

The first flight-test on 7 February 1983 failed due to insufficient cooling of the infrared sensor. Although stainless steel piping had been specified for the ground-based helium supply system, plastic-lined hose had been substituted as a cost-saving measure with the consequence that ambient air molecules contaminated the helium. When blow-down was initiated, the contaminants froze reducing the cooling efficiency so that the desired focal plane temperature was not achieved, resulting in higher sensor internal background noise at the time of target acquisition (Montague email, 03.11.09).

The sensor still functioned sufficiently well to see the target and collect signature data, but because the higher focal plane temperature increased the internal

sensor background noise above the noise rejection threshold, the track file algorithm received too many apparent objects and so no track files were initiated and the sensor did not lock on and activate homing. Ironically, the target was much brighter than expected, but it was simply good fortune that the target remained in the sensor's field of vision and thus allowed useful data to be collected (Montague interview, 11.05.06 and email, 03.11.09).

The second HOE flight test, on 28 May 1983, also missed due to the failure of a guidance system solid-state device, but again provided signature data. The interceptor did successfully acquire the target before this failure and so overall the test was considered a 'successful failure' by the HOE team, although this view was not shared by the Army's hierarchy. When the HOE project leader reported how much they had learned from this test the response was less enthusiastic and to the point: 'If you didn't hit the target, you's a failure' (Interview, 29.11.06).

The third test on 15 December 1983 also missed, but for a different reason again. The software used for the guidance algorithms contained a flaw that inhibited the initiation of the tracking algorithm if the launch command occurred during a particular portion of the airborne computer's cycle time. Although the missile flew out perfectly and the seeker acquired the target, homing guidance was not initiated (Montague interview, 11.05.06 and email, 03.11.09). However, finally, with the credibility of the programme at stake the fourth HOE flight test on 10 June 1984 achieved a direct hit.

Although the public perception at the time was that HOE was part of Reagan's Star Wars programme, this was true only in the sense that the Strategic Defense Initiative (SDI), initiated following Reagan's famous speech of March 23, 1983, had taken on overall management of ballistic missile defence efforts. HOE was an Army programme, and many of the Army's missile defence experts were doubtful of Reagan's apparent aspirations for a perfect shield. However, the

wider scepticism that greeted Reagan's desire for a defence that would make nuclear weapons 'impotent and obsolete' led to HOE being viewed by many as a public relations exercise to bolster SDI funding.

This led to criticism of HOE by BMD opponents on the grounds that a single test success, against one reentry vehicle, with prior warning and no counter-measures, did not demonstrate the feasibility of a nation-wide defence against thousands of Soviet reentry vehicles. This of course was not the intention of HOE's developers whose aim was to determine whether the fundamental technical challenges of hit-to-kill could be overcome. Indeed, the Army press conference the day after the successful test emphasised the experimental rather than operational nature of the technology: 'It's clearly an experiment to see what we could get from this seeker that we built' (GAO, 1994, p. 30). The following April SDI Director Abrahamson described HOE in Senate testimony as 'an experiment that was built on technology and investment that was started a long time ago. It was certainly not weaponized' (GAO, 1994, p. 32).

Further criticism emerged later when, on 18 August 1993, before a Congressional debate on missile defence, the *New York Times* published an article entitled 'Lies and Rigged "Star Wars" Test Fooled the Kremlin, and Congress'. This argued that the HOE test had been rigged because the target warhead carried a beacon that aided interception by providing location data to the defence (Weiner, 1993a). Missile defence supporters countered by pointing out that the beacon was required for range safety radar tracking and was not receivable by the interceptor. The beacon simply provided early flight information to a radar in Hawaii to enable it to provide a sufficiently accurate trajectory for the HOE missile's initial flight path (GAO, 1994, p. 21).

The *New York Times* then argued that the infrared homing was rigged because the target warhead was artificially heated prior to launch (Weiner, 1993b). This heating to 100 degrees Fahrenheit, done for all of the HOE tests, was not

disputed, but its significance was. It meant that the targets were around 14% warmer than they would otherwise have been, but the infrared signatures were still within the range that could be expected from Soviet targets (GAO, 1994, p. 27). Responding in a letter to the *New York Times* (but not published) Dave Montague of Lockheed argued that this heating ensured that all target warheads had a known initial temperature, and the 'difference in visibility to the HOE sensor caused by the pre-heating was negligible' because 'the added temperature dissipated rapidly during flight' as demonstrated by the fact that the target temperature at the time of acquisition by the interceptors on all flights was within 1.5 degrees of unheated targets on later flights.⁴ A much greater contribution to increasing the infrared signatures of the target warheads came from the use of a broadside rather than head-on intercept angle, something that the Army certainly had done to enhance the test's chances of success (GAO, 1994, p. 27). Nevertheless, a Pentagon inquiry ordered by Defense Secretary Les Aspin concluded that 'the experiment was not rigged' (Schmitt, 1993).⁵

Although allegations of deception lingered on amongst BMD opponents (eg Mitchell, 2001), a more typical view was that the HOE test success reflected a genuine technological achievement. However, it was a demonstration of technical feasibility, not military capability. It showed what could be achieved in a flight-test, but not necessarily what could be done in an operational context. In

⁴ Letter from Dave Montague to New York Times, 3 September 1993. Quoted in AIM Report, September 1993, www.aim.org/publications/aim_report/1993/09b.html, accessed 18/1/08.

⁵ There was also a HOE deception programme that was intended to set off an explosion if the interception flew by without hitting the target with the aim of convincing the Soviet Union that the test had been a success. However, this programme had been terminated by the time of the successful fourth HOE test. See GAO (1994). The deception equipment was installed on the first two tests but was not used because neither passed close enough to the target for the deception to be effective.

particular, HOE was not integrated into a missile defence system and did not demonstrate any discrimination of the target from decoys. Nevertheless, the signature data collected by the HOE and DOT programmes convinced HOE's developers that discrimination was feasible.

Hit-to-kill supporters could now point to empirical evidence supporting their claims to epistemic authority. However, not all BMD supporters were convinced. Space-based BMD advocates did not argue the tests were rigged, but instead focussed on in-principle knowledge claims, particularly as regards the challenge of dealing with the large numbers of Soviet warheads. The deployment of MIRV (multiple independently-targetable re-entry vehicle) technology meant each ICBM could carry several warheads, and thousands of Soviet warheads would need even more (to allow for unreliability) US interceptors to counter them. Logic, therefore, pointed to the virtues of interception before the warheads could be released, and thus to space-based systems that could be used 'to break up massive Soviet attacks in the boost-phase' (Davis, 1991, p. 3). Whether HOE worked in a narrow, technical sense was thus irrelevant as space-based BMD advocates argued that only their approach could work in a military sense.

'Star Wars'

This meant that although the successful HOE test had apparently favourable timing, coming a year after President Reagan's March 1983 Star Wars speech, it did not fit into the space-based vision of BMD that dominated SDI. Reagan may have been partly motivated by the administration's political problems, with concern over the growing strength of the Nuclear Freeze movement (Fitzgerald, 2000), but his speech also tapped into growing support for space-based weapons and futuristic technologies (such as lasers and particle beams). At the heart of this new vision for BMD was an old idea - that of boost phase interception of enemy missiles.

The preoccupation with boost-phase defence meant the Reagan administration was lukewarm in its response to the HOE success, even while trumpeting the interception as demonstrating the feasibility of missile defence. Although Secretary of Defense Casper Weinberger noted the significance of HOE by saying 'it will stand as one of the cornerstones upon which the president's Strategic Defense Initiative (SDI) will be built' (quoted in Munn, 1987, p. 43), this transpired not to be the case. The shift of emphasis was clear, as recalled by Weinberger in his memoirs where he noted 'the strong desire we had not to let the programme sink back into a familiar mode of solely ground-based, largely ineffective, defensive systems' (Weinberger, 1990, p. 221).

Hit-to-kill technology still continued. The Exo-atmospheric Reentry Interceptor Subsystem (ERIS) programme was established in July 1984, with Lockheed chosen as the contractor in 1985 (Walker et al, 2003, p. 114). However, between fiscal years 1985 and 1993 ERIS would receive only about half the funding allocated to space-based interceptors and less than a fifth of that spent on directed energy weapons (GAO, 1993, pp. 36-37).

Whereas HOE sought to demonstrate feasibility, ERIS was 'meant to be a working weapon rather than a research tool' (Broad, 1991). HOE had stood alone as a proof of principle, but ERIS was integrated into a defensive concept based around the prevailing thinking of SDI. With the Soviet missile threat comprising thousands of warheads it was argued that an interceptor such as ERIS must be economical if sufficient were to be procured. According to the ERIS programme manager, ERIS was 'only a very cheap – if I can use that word – version of what HOE was. The name of the game is to make it affordable' (quoted in Reiss, 1992, p. 120).

Even more significantly, SDI favoured the use of space-based systems, and crucially ERIS was designed to rely on external sensors (including 'Brilliant Eyes' satellites with infrared sensors) for discrimination and to put the interceptor on to

the correct trajectory. In this defensive concept the interceptor 'would be guided towards the target by the external sensor (e.g. Brilliant Eyes) and would be told which object in its field of view is the actual target' (GAO, 1992, p. 18). The intention was that these sensors would provide a hand-over to ERIS with at least one meter accuracy and that ERIS itself would be a relatively 'dumb interceptor' (Interview, 29.11.06).

This meant that ERIS did not need such a long-range sensor as HOE, allowing a change in technology, with Mercad rather than silicon used for the focal plane. Consequently, the operating temperature did not need to be so low and liquid nitrogen rather than troublesome helium could be used for the cooling system. In addition, the sensor did not need to be pre-cooled as a sufficiently low temperature could be achieved by blow-down during flight.

The first ERIS test on 28 January 1991 was described as 'an unqualified success', with the interceptor hitting the target warhead between two balloon type decoys (Broad, 1991). Because adequate space-based sensors such as Brilliant Eyes were not yet deployed (and still were not twenty years later), the hand-over function was simulated by the use of Global Positioning System satellites which provided the tracking information to direct the interceptor towards the threat cluster. Similarly, with no external sensors capable of discrimination available the interceptor was pre-programmed to select the middle of three objects that comprised a dummy reentry vehicle with a balloon decoy on either side of it. The interceptor was able to see these objects with its infrared sensor and accordingly manoeuvred to hit the middle one (GAO, 1992, pp. 22-23). However, a later investigation by the General Accounting Office deemed that claims that the kill vehicle carried out successful discrimination were over-stated. The kill vehicle simply followed its instructions to hit the middle object, but did not do so by choosing the appropriate infrared signature, and if a decoy had mistakenly ended up in the middle, the kill vehicle would have hit that instead (GAO, 1992, p. 23).

A second, more ambitious test was carried out on 13 March 1992. As well as attempting to intercept the target, the test was also designed to demonstrate the interceptor's ability to use one-colour (i.e. one frequency band) infrared signatures to distinguish between the target and a decoy, and to collect two-colour infrared data by tracking the decoy balloon. The test was designed so that the target reentry vehicle and decoy would initially be close together, appearing as one object to the interceptor when it first detected them. As the interceptor closed on the target cluster the reentry vehicle and decoy would resolve into two objects and the interceptor was programmed to select the object with the lowest infrared signature (the cooler object, the reentry vehicle). The interceptor then used a pre-programmed amount of time to collect two-colour infrared data on both objects before attempting to intercept the target. The amount of time allocated for tracking the decoy, and therefore the amount that would be left for the intercept to home onto the target, was based on the rate of separation between reentry vehicle and decoys seen in previous tests. Unfortunately, in this test the decoy deployed much faster than before and by the time the interceptor switched its attention to the target, it had too little time left to achieve the necessary divert with the result that it missed (GAO, 1992, pp. 24-26 and Interview 29.11.06).

ERIS was one element of a deployment plan set out by SDI in the 1987 Strategic Defense System Phase 1. This envisaged a layered defence with both space and ground-based interceptors intended to counter some of the Soviet ballistic missile threat – it was not the impervious shield that Reagan had originally hoped for - but even then SDI had difficulty producing an affordable implementation plan (Fitzgerald, 2000, pp. 406-7). The Soviet missile threat was simply too great to be countered by any defence that the US Congress was prepared to pay for.

Recognising this political reality, and the changes occurring in the Soviet Union, some BMD supporters – including Republican Senators Warner, Cohen, and

Lugar (Schmitt, 1991) – suggested that SDI begin with a more modest ground-based interceptor deployment. SDI resisted such proposals (Davis, 1991, p. 2):

The Phase I architecture, the centerpiece of the program for four years, was defended by the program office and the administration far after it's [sic] credibility as a defense against a massive Soviet attack had evaporated. ... congressional initiatives for a more modest first step were met by a stone wall of politically damaging defiance within the administration, largely based on the fear that a smaller first step may be the last step. ... The fear of a more limited initial defense has fed on the presumption that the deployment of space-based weapons, the key element in the Phase I architecture and the symbol of Star Wars legitimacy, may never gain political acceptance if it were not a part of the first step ...

However, although the threat was about to change dramatically with the breakup of the Soviet Union, partly undermining the rationale for boost-phase interception, the BMD concept would continue to reflect SDI's space-based emphasis.

Post-Cold War Missile Defence

Announced by President Bush in his January 1991 State of the Union speech, SDI's post-Cold War vision for strategic BMD, known as Global Protection Against Limited Strikes (GPALS), had a 'continued insistence on early deployment of space-based weapons' (Davis, 1991, p. 3). The rationale for GPALS was to provide protection against up to 200 reentry vehicles launched from anywhere in the world, either from rogue states or from accidental launches (with particular concern about the former Soviet Union's arsenal). A key technology, strongly favoured by new SDI Director Henry Cooper,⁶ was the Brilliant Pebbles space-based interceptor system. Ground-based interceptors

⁶ Cooper was SDI Director from July 1990 to January 1993, but had earlier carried out a review of BMD policy for the Bush administration in which he recommended the shift to GPALS.

(GBIs), designed to counter both strategic and theatre threats, were also included, but did not receive high-level advocacy as Cooper believed that 'because of the global coverage of such space systems, it was clear that Brilliant Pebbles would be the lowest cost and the most militarily effective means of defending both the United States and our overseas troops, friends and allies' (Cooper, 2000).

Rather than deploy an ERIS-based GBI, SDI's preference was for a competitor technology known as LEAP (lightweight exo-atmospheric projectile) because Cooper's preoccupation with space-based BMD engendered a belief that smaller was better, and they therefore 'wanted to work on teeny, tiny kill vehicles' (Montague interview, 11.05.06). While announcing the success of the first ERIS flight test, SDI was already talking about a future interceptor the size of a 'breadbox' (McMahon, 1997, p. 94). LEAP took the obsession with small size to extremes, with kill vehicles weighing as little as thirteen pounds (GAO, 1992, p. 27). However, to get this small size required exotic materials and 'a watch maker's job', making LEAP expensive and unsuitable for production in large quantities (Interview, 29.11.06). Support for ERIS development was thus undermined because 'there was still this competition amongst the technology people and the various groups as to whether ERIS was the way to go or whether LEAP was the way to go or whether we needed to start all over' (Interview, 29.11.06). In the end, the latter course was chosen, with neither ERIS nor LEAP remaining in development by the Army.⁷

In May 1991 Cooper testified that he believed that GPALS could form 'the basis for common ground regarding SDI with the Congress, our allies and friends, and the Soviets' (quoted in McMahon, 1997, p. 97). This proved not to be the case,

⁷ The LEAP technology was transferred to the Navy in 1993 and formed the basis for the development of the Terrier/LEAP programme which evolved into the exo-atmospheric interceptor now based on Aegis ships (Walker et al, 2003, p. 123).

but common ground was developing in Congress, albeit around a technological approach different from that favoured by Cooper. This marked a turning point in BMD history with Congress making a decisive shift away from the space-based vision favoured by SDI, and towards concrete plans for deployment of hit-to-kill GBIs.

The use of the short-range Patriot defensive missile against Iraqi Scuds in the 1991 Gulf conflict proved a key development. Republican missile defence supporters in Congress moved to build a consensus around two 'lessons' that were seen to bolster the argument for BMD (McMahon, 1997, pp. 106-07). First, without Patriot, US forces, as well as allies, would have had no protection from Iraq's Scud missiles. Second, the fact that Saddam Hussein had used these missiles against US forces, and also against Israel, showed that deterrence could not be relied on, an especially worrying thought if combined with Iraq's nuclear ambitions.

Although claims about Patriot's effectiveness in the first Gulf War were strongly disputed (Postol, 1991/92), these arguments had a powerful resonance for the general principle that it was undesirable to leave the US and its forces and allies defenceless. Further support came with the events of August 1991, when the attempted coup in the Soviet Union, followed by the start of the break-up of the Soviet Union, led to concerns over the effectiveness of controls of Soviet nuclear forces. After much compromise the 1991 Missile Defense Act was passed by Congress in November, and President Bush signed it into law. The main thrust of the Act was that the 'Department of Defense shall develop for deployment by the earliest date allowed by the availability of appropriate technology, or by 1996, a cost effective, operationally effective, and ABM Treaty-compliant BMD system' (McMahon, 1997, p. 112).

GBI hit-to-kill technology was now the preferred option. The successful intercepts achieved in HOE and ERIS showed that hit-to-kill was possible, but an

operational system still needed to be developed and built, and in particular the key issue of discrimination needed to be addressed. Although Brilliant Pebbles was removed from the deployment plan, the space-based sensors of the Brilliant Eyes (BE) satellites remained central. SDI's July 1992 Report to Congress noted the role of Brilliant Eyes thus: 'BE develops high quality tracks and provides early discrimination shortly after the reentry vehicles drop off the post-boost vehicle' (SDIO, 1992, p. 2-10). The reliance on Brilliant Eyes thus reflected a compromise between ground and space-based approaches. The next generation of GBI would incorporate an exo-atmospheric kill vehicle (EKV) design predicated on a concept that emphasised discrimination by space-based satellites. This would prove controversial within the hit-to-kill community, not only because of the organizational distaste towards space-based systems, but also because they believed on-board EKV discrimination had better prospects.

EKV Development and Deployment under Clinton and G. W. Bush

Initially, however, the new administration of Bill Clinton (elected at the end of 1992) downplayed the importance of strategic BMD. On 13 May 1993 Secretary of Defense Aspin, announced the 'end of the Star Wars era', changing the name of the organisation in charge of missile defence from SDI to the Ballistic Missile Defense Organisation (BMDO). With the lessons of the Gulf War in mind, the emphasis was now to be on theatre BMD (McMahon, 1997, p. 245).

However, the midterm elections of 1994 produced a hostile Republican dominated Congress, resurrecting what was now termed National Missile Defence (NMD) as a political issue. The result was further Congressional legislation, the 1995 Ballistic Missile Defense Act. Like its 1991 predecessor, the 1995 Act sought deployment of a BMD system using ground-based interceptors to protect the United States, with sensors both ground-based and in space. Unlike the earlier act, the 1995 Act specified a deployment timetable, setting 2003 as the date for an initial operational capability. This was vetoed by Clinton,

but the resulting compromise led to a doubling of spending on strategic missile defence (Graham, 2001, p. 26).

Further political pressure came with the 1998 publication of the Rumsfeld Commission report on ballistic missile threats from so-called rogue states, and its impact was amplified by the launch of a three-stage missile by North Korea that August (Graham, 2001, pp. 52-69). Although the missile did not in itself constitute much of a threat to the US mainland, it did indicate that North Korea was making progress in missile development, and even more significantly to some, that US intelligence agencies could not be relied on to predict potential threats.

Meanwhile EKV work continued. After a number of mergers between companies, the final competition was between teams from Boeing (formerly Rockwell) and Raytheon (formerly Hughes). A key difference between the two centred on the choice of focal plane material, with Boeing using the same silicon approach as HOE, whereas Raytheon took the ERIS approach of using Mercad Telluride. During the contest Boeing highlighted a graph that stressed the advantages of silicon's greater sensitivity over a wider range of frequencies: 'They [Boeing] would show that - that was always their big curve, went out to 20 and showed Mercad cutting off at 12 - when they were selling silicon' (Interview, 29.11.06). This meant that silicon offered longer acquisition range, which in turn, meant that the EKV could be lined up with the target earlier and so needed to carry less propulsion for diverts. However, this weight advantage could be outweighed by the challenge of cooling the silicon focal plane to the required 10 degrees Kelvin (Interview, 29.11.06). Nevertheless, the Boeing design was still simpler than Raytheon's which used three separate focal planes to detect different wavelengths, and thus required plumbing to cool each of these individually.

In the end the perceived qualities of the two firm's different EKV designs would not decide the competition, which was abruptly curtailed in December 1998 when

Raytheon was awarded the contract 'after Boeing disclosed to the government that employees of its EKV team had obtained and misused proprietary information developed by the other EKV competitor, Raytheon' (GAO, 2003a, p. 2; see also Graham, 2001, pp. 181-185). Raytheon thus got the EKV job by default (see Figure 2).

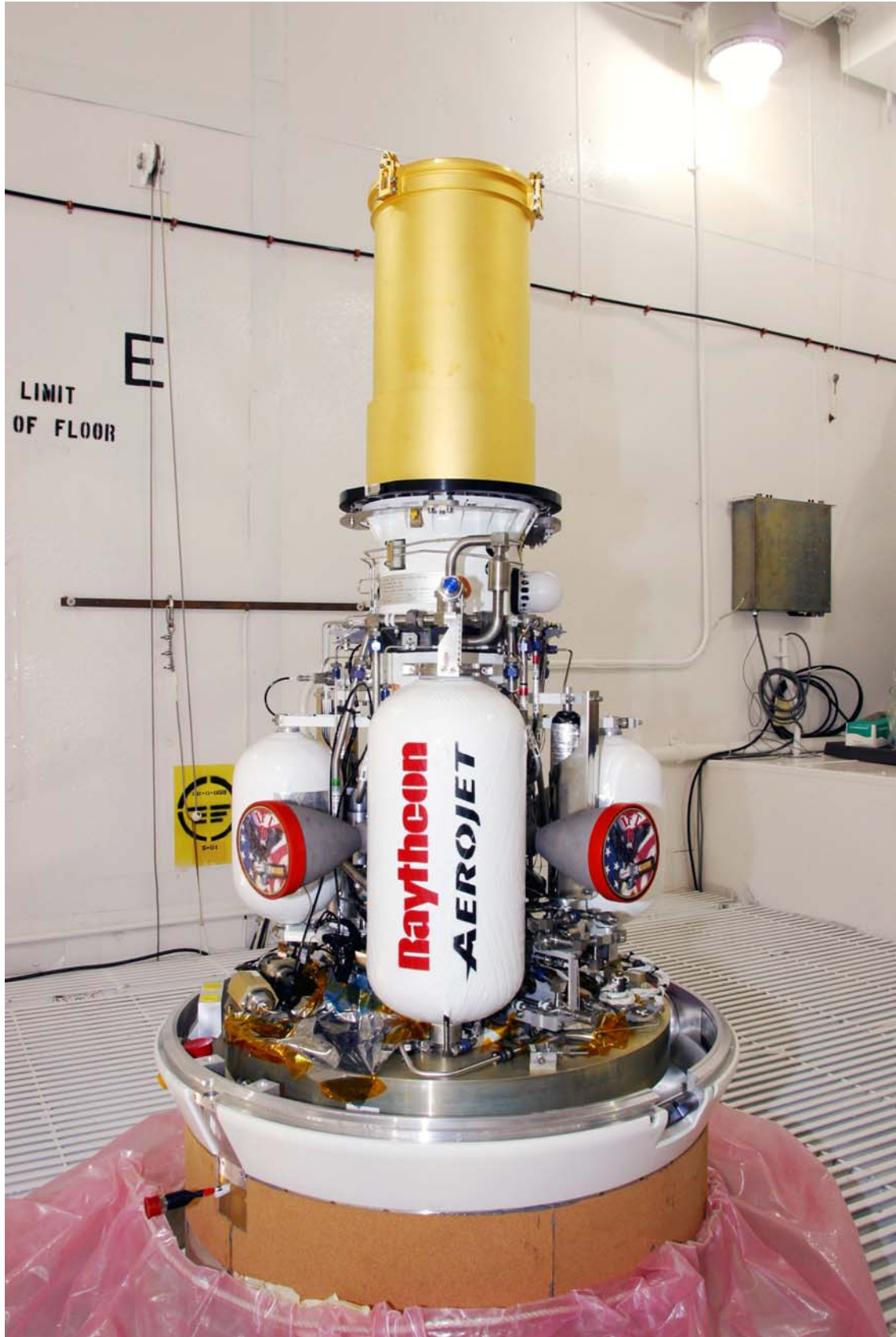


Figure 2: The Raytheon Exo-Atmospheric Kill Vehicle. Photograph reproduced with permission of the US Missile Defense Agency.

What had been a small technology readiness project now became a high profile development programme, and Raytheon's inexperienced team struggled to produce an EKV suitable for flight-testing (Graham, 2001, p. 186). Nevertheless the first flight-test on October 2, 1999 – with an EKV said to be about 120 pounds in weight and four feet long (Broad, 1999) - achieved a direct hit, albeit somewhat fortuitously.⁸ However, the following two tests both failed to hit the target (Becker, 2000). In the first the sensor failed to cool sufficiently, probably due to faulty plumbing, and in the second the EKV failed to separate from the booster (Sciolino, 2000b; Graham, 2001, pp. 301-02). With the maturity of the technology unproven, Clinton was able to defer the deployment decision to the next US president (Schmitt, 2000).

Whereas Clinton had at best been lukewarm, the election of George W. Bush saw a shift towards deployment. The hit-to-kill technology of the NMD program - renamed as the Ground-based Midcourse Defence (GMD) - now became the mainstay of US missile defence plans. The Bush administration was determined to press ahead quickly and GMD testing became geared towards development and deployment rather than demonstrating feasibility. The Missile Defense Agency (MDA), as BMDO was renamed, adopted a capability-based approach. That is to say, MDA began deployment of the best available technology more or less regardless of test results. Indeed, a series of failures meant that no flight-tests were carried out between October 2002 and September 2006 (Spinardi, 2008).

⁸ The EKV initially drifted off course and locked on to a decoy balloon rather than the target warhead. See Sciolino (2000a).

The original plan for a system based at the old Safeguard site in North Dakota (and thus compliant with the ABM Treaty) proved unworkable politically because missiles based there could not provide complete protection of the most western Aleutian Islands off Alaska or two uninhabited Hawaiian islands (Graham, 2001, pp. 123-26). This mattered because the Republican Senator Ted Stevens of Alaska was the chairman of the powerful Senate Appropriations Subcommittee on Defence, and Senator Daniel K. Inouye of Hawaii was the ranking democrat on that subcommittee (Gordon and Myers, 2000). In order to achieve complete coverage a long-burn booster was chosen to launch the EKV, a design choice that was compatible with the EKV's short viewing range.

This was seen as appropriate because the design of the EKV was predicated on the availability of space-based infrared discrimination. This technical choice reflected the space-based bias of the Star Wars era and the expectation that space-based sensors would provide high quality target data, thus reducing the need for the interceptor to have a long time to view the target. The idea was that 'we're going to have this satellite that's going to tell you very accurately: a. what the target is and b. where it is. So you can look through a soda straw and you don't have to start looking until it's perhaps 100 kilometers away, as opposed to close to a thousand' (Montague interview, 11.05.06 and email, 03.11.09).

As it turned out, these space-based sensors were delayed, with the SBIRS-High programme (the successor to Brilliant Eyes) suffering technical problems and cost and schedule overruns (GAO, 2003b; Smith, 2005). The first satellite was finally launched in May 2011, but until a complete system is deployed and tested the GMD system must rely on discrimination using target data from a combination of ground-based radar and the EKV's own infrared sensor. By 2011 30 GMD interceptor missiles had been deployed (26 based in Alaska and 4 in California), but serious doubts remain about the operational effectiveness of this technology.

Of the 16 attempted intercept tests of the EKV technology up to 2010, only 8 were described as fully successful. One failed attempt was dubbed a no test because the failure of the target to deploy properly meant that the interceptor was not launched, there was one failure of the EKV to cool properly, in two cases the interceptors failed to take off at all, and in two other cases the EKV failed to separate from the missile. The latest two tests in January and December 2010 both failed to hit the target, with the first miss attributed to a radar problem (Coyle, 2010) and the latter failure reason as yet undisclosed.⁹

Testing, Design Choices, and the Debate over GMD Feasibility

The current GMD system has been shaped in part by the space-based bias of the SDI era, in part by the political necessity to protect all US territory (including Hawaii), and in part by the circumstances that disqualified Boeing from the competition for the EKV contract. It has proved politically sustainable (the Obama administration continued its deployment), but many critics continue to question its technical feasibility, not least because of its middling flight-test record.

These critics can point to a flight-test success rate of only 50% hitting the target. The most recent test failure in December 2010 led the MDA to suspend EKV production, pending the results of reviews and further tests (O'Reilly, 2011). Although the 1984 HOE intercept showed that hit-to-kill was feasible in test conditions, subsequent testing has not yet produced a consensus that this can be achieved consistently or in real-world conditions.

Many critics of the GMD system, such as the Union of Concerned Scientists, argue that not only have the flight-tests not achieved sufficiently good results to justify deployment, but also that they have been insufficiently similar to operational use. Any inference of real-world performance is therefore unjustified.

⁹ The system was reported to have functioned perfectly until the last 20 seconds of EKV flight, but what went wrong has not been reported. See Butler, 2011.

Central to the real-world capability of the GMD system is the ability of the EKV to discriminate warheads from decoys, but many question whether this is possible, and argue that the flight-tests that have been carried out do not demonstrate such a capability.

For example, the UCS argues that the tests of the NMD/GMD technology have been insufficiently realistic because they have been carried out over a limited number of intercept trajectories, without much variation in the position of the sun, against unchallenging or no countermeasures, and with prior knowledge of the nature and timing of the attack (Gronlund et al, 2004). This criticism thus focuses on similarity judgements (MacKenzie, 1989) about whether the tests were sufficiently similar to operational use.

However, this history of hit-to-kill technology shows that doubts about GMD feasibility are not restricted to BMD opponents, and do not just hinge on this matter of inference from test results. Instead, two groups of BMD supporters also doubt GMD feasibility, though for markedly different reasons. Moreover, their doubts revolve around a dispute about epistemic authority deriving from differing types of knowledge claims.

Supporters of space-based BMD have always claimed epistemic authority on the basis of deduction from conceptual analysis (no such systems have reached the stage of flight-testing). This space-based BMD lobby supports the deployment of missile defences, but argues that midcourse hit-to-kill is the wrong approach *in principle*. They argue, for example, that 'GMD is a limited midcourse defense that will be effective against only a few missiles with simple decoys. Because GMD cannot adequately discriminate among midcourse threats, it may be prone to failure unless it becomes part of a layered missile defense' (Independent Working Group, 2006. p. 15). Supporters of space-based BMD thus continue to advocate a satellite-based system for boost-phase interception.

In contrast, some supporters of ground-based hit-to-kill BMD also criticise the current GMD system, but base their knowledge claims about feasibility on both conceptual *and* empirical grounds. These critics comprise many with direct experience of early hit-to-kill development (such as HOE and DOT) who believe that the implementation of hit-to-kill technology in the GMD design has been undermined by reliance on space-based sensors for discrimination. Their claims to epistemic authority thus derive from their hands-on experience with developing and testing hit-to-kill technology.

The central objection of these critics is not that GMD flight-testing is unrepresentative (although they would endorse more challenging tests), but rather that the effectiveness of the technology has been undermined by the adoption of an operational model based on the use of satellite sensors to provide discrimination. These critics lament the fact that the emphasis on space-based sensors means that the GMD programme has not built on the infrared data collected from earlier tests, including HOE and DOT, and that discontinuation of this work meant that 'expertise was lost' (NRC 2012, p. 131). As a consequence: 'Forty years of optical signature data from well-instrumented past and recent flight tests are lying fallow and unanalyzed with respect to current technological capabilities' (NRC 2012, p. 12).

The key concern is that the EKV has been designed to have too short a viewing time because of its limited range infrared sensor and the long-burn time of the rocket boosters used to launch it. A short viewing time has two main consequences. It means less time for the EKV sensor to gather signature data that might enable discrimination, and it also limits the 'battle space' as regards the defence having a second chance should the first intercept attempt fail. The lack of time is critical because the potential for discrimination depends on the ability of the EKV to watch target objects as their infrared signatures change as they pass through varying conditions. As the Lockheed manager of the HOE programme puts it: 'Time is the key discriminant because everything varies with

time' (Montague interview, 11.05.06). Although such discrimination is very challenging, it is claimed that 'Lincoln Laboratory ... has worked out some very powerful algorithms that are based ... on the thermodynamics of looking at the body, but it takes a while - you can't do it with the EKV in ten seconds' (Davis interview, 29.11.06).

Given time it is argued that the EKV (if it has sufficient sensor range) can view the target and carry out discrimination because of the changing thermodynamic behaviour of objects as they move through differing conditions of incident radiation (for example, moving between night and day and moving over land or ocean). As ambient radiation changes, lighter weight objects undergo greater temperature shifts than heavier objects and so similar shaped objects of different mass, which radar cannot readily distinguish in the atmosphere-free midcourse, could be discriminated due their fluctuating infrared signatures. However, according to disgruntled hit-to-kill supporters, this on-board EKV discrimination is not possible in the current GMD design, and instead 'they're relying primarily on X-band radar for real discrimination because the viewing time of the kill vehicle is very short' (Montague interview, 11.05.06 and email, 03.11.09).

In addition to objecting to its 'myopic' sensor, the insider critics also regret the choice of a long-burn booster for the GMD system. As one put it: 'Because Boeing didn't understand the problem and they got helped by the BMDO to create this requirement to defend Hawaii from someplace in the United States - you got this humungous reach requirement that makes no sense at all' (Interview, 11.05.06). The problem with this is that the 'interceptor cannot do anything until it burns out and so if you've got this thing in a long boost its just eating up battle space while its trying to get to its burnout point' (Mead interview, 29.11.06). This means that should the interception fail there would be no time for a second attempt, and information obtained by a first wave of defensive interceptors cannot be passed to a second wave.

These formerly-marginalised insider critiques finally became mainstream in 2012 with the publication of an authoritative study carried out under the auspices of the National Academy of Sciences in response to a Congressional request. This study describes deficiencies with the current GMD system, particularly as regards its combination of long burn and short viewing times, and concludes that: 'The GMD system lacks fundamental features long known to maximize the effectiveness of a midcourse hit-to-kill defense capability against even limited threats' (NRC 2012, p. 131). Instead the study recommends 'a smaller, shorter burn interceptor' missile with 'a heavier, more capable kill vehicle', and a combination of long viewing times (over 100 seconds) and X-ray radar data for discrimination. (NRC 2012, pp. 131-32). Were these recommendations to be accepted as policy, the tale would have come full circle, and the veterans of early hit-to-kill development (some of whom were authors of the study) would have seen their epistemic authority accepted as most credible.

Conclusion

Despite many years of development and testing, claims about the performance of hit-to-kill technology remain contested. A superficial analysis of this would see a straightforward dichotomy based on social interests. On the one hand, the MDA sees flight-tests as providing useful feedback on performance, with a commitment to conduct 'increasingly complex flight tests to achieve more objectives and enhance the realism of each test' (O'Reilly, 2011). On the other hand, BMD opponents argue that GMD testing has been insufficiently realistic to provide a guide to real-world feasibility. For example, in 2008 David Wright of the UCS dismissed the value of an upcoming test, arguing that: 'Successful or not, this test will not prove that the missile defense system can counter real-world decoys' (Wright, 2008).

However, the detailed history of hit-to-kill technology described here shows that concerns about hit-to-kill feasibility are more complex than this. These concerns

are not restricted to traditional BMD opponents, but also include supporters, including many veterans of hit-to-kill development. For these critics the issue rests not on the similarity judgments involving comparison between tests and real world use, but also on judgments about what real world use would involve, and thus what comprises the best BMD system design.

These judgments have intertwined with organisational allegiances to produce two main camps of BMD supporters: one supporting midcourse interception by ground-based missiles, the other aligned with space-based systems for boost-phase interception. The lack of operational experience, the changing and contested nature of the threat, and the highly political (in terms of both party and bureaucratic politics) nature of the issue, have made closure hard to achieve, and often transitory. In this terrain, the historical turf-battle between the Army and the Air Force has evolved over the years into a battle for epistemic authority hinging on different types of knowledge claims.

Not always obvious to the general public, this dispute over epistemic authority has been central to the evolution of US BMD technology. Space-based advocates had their day in the 1980s with Reagan's Star Wars, but over the last two decades the pendulum has swung decisively towards advocates of ground-based interceptors. However, some hit-to-kill old-timers were unhappy because they considered the technology developed – the GMD system – to be a compromise outcome, shaped by the politics of the Star Wars era, amongst other things.

Whether the recent National Academy of Sciences study will settle the matter once and for all is open to question. The history of BMD shows protracted argument over more than fifty years, not just about which technological solution would work best, but also about what type of knowledge should carry most credibility. The technology of concern here – for defence against nuclear-armed ballistic missiles – is unusual in its complete lack of operational use. Whether

such use would provide compelling evidence is hard to know (data collection might be a problem), but it is sincerely to be hoped that the need for such use does not occur.

Acknowledgements

I am extremely grateful to those I interviewed for this paper, particularly Bill Davis and Dave Montague, for kindly giving up their time to me, and for their further advice on drafts. I am also grateful for very helpful comments on drafts by Donald MacKenzie and Rebecca Slayton. This research was funded by the UK Economic and Social Research Council.

References

Abraham, John and Julie Sheppard (1999) 'Complacent and Conflicting Scientific Expertise in British and American Drug Regulation: Clinical Risk Assessment of Triazolam', *Social Studies of Science*, Vol. 29, No. 6 (December), 803-43.

Armacost, M. H. (1969) *The Politics of Weapons Innovation: The Thor-Jupiter Controversy* (New York: Columbia University Press).

Barber Associates, The Advanced Research Projects Agency, 1958-1974 (Washington, December 1975).

Becker, Elizabeth (2000) 'Missile is Unable to Hit its Target in Pentagon Test', *New York Times* (19 January).

Bloor, David (2006) 'Towards a Sociology of Epistemic Things', *Perspectives on Science*, Vol. 13, No. 3, 285-312.

Bloor, David (2011) *The Enigma of the Aerofoil: Rival Theories in Aerodynamics, 1909-1930* (University of Chicago Press).

Broad, William J. (1991) 'In Test, "Star Wars" Picks off a Warhead in Space', *New York Times* (30 January).

Broad, William J. (1999) 'After Many Misses, Pentagon Still Pursues Missile Defense', *New York Times* (24 May).

Butler, Amy (2011) 'Target of Praise', *Aviation Week & Space Technology*, September 19, p. 60.

Cooper, Henry F. (2000) Letter to Senator John Warner (July 31).

Coyle, Phil. (2010) 'Latest Ground-based Midcourse Defense (GMD) System Test', Center for Defense Information, 2 February.

Dao, James (2001) 'Amid Applause, Caution Urged on Missile Defense', *New York Times* (16 July).

Davis, Bill (1991) *KEW Responsive Threat Analysis* (Scientific Services Program, for US Army Missile & Space Command).

Downer, John (2007) 'When the Chick Hits the Fan: Representativeness and Reproducibility in Technological Tests', *Social Studies of Science*, Vol. 37, No. 1, 7-26.

Fitzgerald, Frances (2000) *Way Out There in the Blue: Reagan, Star Wars and the End of the Cold War* (Touchstone).

GAO (General Accounting Office) (1992) 'Strategic Defense Initiative: Some Claims Overstated for Early Flight Tests of Interceptors', GAO/NSIAD-92-282, (September).

GAO (1993) 'Ballistic Missile Defense: Evolution and Current Issues', GAO/NSIAD-93-229 (July).

GAO. (1994) 'Ballistic Missile Defense: Records Indicate Deception Program Did Not Affect 1984 Test Results', GAO/NSIAD-94-219 (July).

GAO (2003a) Letter from Anthony H. Gamboa, General Counsel, GAO to Howard L. Berman, House of Representatives, January 27, 2003. GAO-03-324R-Missile Defense.

GAO. (2003b) Defense Acquisitions: Despite Restructuring, SBIRS High Program Remains at High Risk of Cost and Schedule Overruns, Report to the Subcommittee on Strategic Forces, Committee on Armed Services, US Senate, GAO-04-48 (October).

Gordon, Michael R. and Steven Lee Myers (2000) 'The Nuclear Shield: Looking for Cover; Politics Mixes With Strategy In Plan for Antimissile System', *New York Times* (23 June).

Graham, Bradley (2001) *Hit to Kill: The New Battle Over Shielding America from Missile Attack* (New York: Public Affairs).

Greenwood, Ted (1975) *Making the MIRV: A Study of Defense Decision Making* (Ballinger).

Gronlund, L., D. Wright and S. Young (2001) 'An Assessment of the Intercept Test Program of the Ground-based Midcourse National Missile Defense System' (Union of Concerned Scientists Working Paper, 30 November).

Gronlund, L., D. Wright, G. Lewis and P. Coyle (2004) *Technical Realities: An Analysis of the 2004 Deployment of a US National Missile Defense System* (Cambridge, MA: Union of Concerned Scientists, May).

Independent Working Group (2006) *2007 Report' on 'Missile Defense, the Space Relationship, & the Twenty-First Century*, sponsored by the American Foreign Policy Council. Available at www.ifpa.org/publications/IWGReport.htm.

Kadish, Lieutenant General Ronald T., 2001 Director, Ballistic Missile Defense Organization Statement Before the House Armed Services Committee, Subcommittee on Military Research & Development, Thursday, June 14, 2001.

Levidow, Les (2001) 'Precautionary Uncertainty: Regulating GM Crops in Europe', *Social Studies of Science*, Vol. 31, No. 6 (December), 842-74.

Mackenzie, Donald (1989) 'From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy', in D. Gooding, T. J. Pinch and S. Schaffer (eds), *The Uses of Experiment* (Cambridge University Press), 409-436.

Mackenzie, Donald (1990) *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (MIT Press).

MacKenzie, Donald (1996) 'How Do We Know the Properties of Artefacts? Applying the Sociology of Knowledge to Technology', in R. Fox (ed.), *Technological Change: Methods and Themes in the History of Technology* London: Harwood, 247-263.

McMahon, K. Scott (1997) *Pursuit of the Shield: The US Quest for Limited Ballistic Missile Defense* (University Press of America).

Mitchell, Gordon R. (2001) *Strategic Deception: Rhetoric, Science and Politics in Missile Defense Advocacy* (Michigan State University Press).

Munn, Michael (1987) 'The Homing Overlay Experiment: A Major Step in Ballistic Missile Defense', *Lockheed Horizons*, Issue 23 (April).

National Research Council (NRC) (2012) *Making Sense of Ballistic Missile Defense: Assessment of Concepts and Systems for US Boost-Phase Missile Defense in Comparison to Other Alternatives* (National Academies Press, 2012).

O'Reilly, Lt. General Patrick (2011) Statement of Director of Missile Defense Agency before the Senate Appropriations Committee, Defense Subcommittee, May 25.

Peoples, Columbia 2009 *Justifying Ballistic Missile Defence* (Cambridge University Press).

Pinch, T. (1993) "'Testing – One, Two, Three ... Testing!'" Towards a Sociology of Testing', *Science, Technology & Human Values*, Vol. 18, No. 1, 25-41.

Postol, Theodore A. (1991/92) 'Lessons of the Gulf War Experience with Patriot', *International Security*, 16(3) (Winter), 119-171.

Price, Stephan D. (2009) 'Infrared Sky Surveys', *Space Science Review*, Vol. 142, 233-321.

Reiss, E. (1992) *The Strategic Defense Initiative* (Cambridge University Press).

Sapolsky, Harvey (1972) *The Polaris System Development: Bureaucratic and Programmatic Success in Government* (Harvard University Press).

Schmitt, Eric (1991) '3 Republicans Break with Bush over "Star Wars"', *New York Times* (16 June).

Schmitt, Eric (1993) 'Aspin Disputes Report of "Star Wars" Rigging', *New York Times* (10 September).

Schmitt, Eric (2000) 'Clinton's Missile Decision: The Overview; President Decides to Put Off Work on Missile Shield', *New York Times* (2 September).

Sciolino, Elaine (2000a) 'Pentagon Gives a Preview of Missile Defense Test Tomorrow', *New York Times* (6 July).

Sciolino, Elaine (2000b) 'Key Missile Parts Are Left Untested as Booster Fails', *New York Times* (9 July).

SDIO [Strategic Defense Initiative Organization] 1992 '1992 Report to Congress on the Strategic Defense Initiative', (July).

Sessler, Andrew M., John M. Cornwall, Bob Dietz, Steve Fetter, Sherman Frankel, Richard L. Garwin, Kurt Gottfried, Lisbeth Gronlund, George N. Lewis, Theodore A. Postol and David C. Wright (2000) *Countermeasures: A Technical Evaluation of the Operational Effectiveness of the Planned US National Missile Defense System*, Union of Concerned Scientists and MIT Security Studies Program, Cambridge, Mass.

Slayton, Rebecca (2003) 'Speaking as Scientists: Computer Professionals in the Star Wars Debate', *History and Technology*, Vol. 19, No. 4, 335-364.

Smith, Marcia S. (2005) *Military Space Programs: Issues Concerning DOD's SBIRS and STSS Programs*, CRS Report for Congress, RS21148, (Congressional Research Service, Report to Congress, May 20).

Spinardi, Graham (1994) *From Polaris to Trident: The Development of US Fleet Ballistic Missile Technology* (Cambridge University Press).

Spinardi, Graham (2008) 'Ballistic missile defence and the politics of testing: the case of the US Ground-based Midcourse Defence' *Science & Public Policy*, 35(10), December, 703-715.

Spinardi, Graham (2010) 'The Rise and Fall of Safeguard: Anti-Ballistic Missile Technology and the Nixon Administration,' *History and Technology*, Vol. 26, Issue 4 (December), 313-334.

Stevenson, Richard W. (1999) 'Missile System Passes a Test As a Target Is Destroyed', *New York Times* (October 4).

Walker, James, Lewis Bernstein and Sharon Lang (2003) *Seize the High Ground: The Army in Space and Missile Defense* (Historical Office, US Army, Space and Missile Defense Command).

Weinberger, Casper (1990) *Fighting For Peace* (Grand Central Publishing).

Weiner, Tim (1993a) 'Lies and Rigged "Star Wars" Test Fooled the Kremlin, and Congress', *New York Times* (18 August).

Weiner, Tim (1993b) 'General Details Altered "Star Wars" Test', *New York Times* (27 August).

Wright, David (2008) 'UCS Backgrounder: Missile Defense Test FTG-05' (December).

<http://www.ucsusa.org/assets/documents/nwgs/MissileDefenseTestBackgrounder-12-4-08.pdf> Downloaded 9/1/12.

Yanarella, Ernest J. 1977 *The Missile Defense Controversy* (University Press of Kentucky).